SIMULATION OF IMPACT AND FRAGMENTATION WITH THE MATERIAL POINT METHOD

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ABSTRACT

The simulation of high-rate deformation and failure of metals is has traditionally been performed using Lagrangian finite element methods or Eulerian hydrocodes. Lagrangian mesh-based methods are limited by issues involving mesh entanglement under large deformation and considerable complexity in handling contact. On the other hand, Eulerian hydrocodes are prone to material diffusion. In the Material Point Method (MPM), the material state is defined on solid Lagrangian particles. The particles interact with other particles in the same body, with other solid bodies, or with fluids through a background mesh. Thus, some of the problems associated with finite element codes and hydrocodes are alleviated. Another attractive feature of the material point method is the ease with which large deformation, fully coupled, fluid-structure interaction problems can be handled. In this work, we present MPM simulations that involve large plastic deformations, contact, material failure and fragmentation, and fluid-structure interaction.

The plastic deformation of metals is simulated using a hypoelastic-plastic stress update with radial return that assumes an additive decomposition of the rate of deformation tensor. The Johnson-Cook model and the Mechanical Threshold Stress model are used to determine the flow stress. The von Mises and Gurson-Tvergaard-Needleman yield functions are used in conjunction with associated flow rules. Failure at individual material points is determined using porosity, damage and two bifurcation conditions - the Drucker stability postulate and the acoustic tensor check for loss of hyperbolicity. Particles are converted into a new material with a different velocity field upon failure. Impact experiments have been simulated to validate these models using data from high strain rate impact experiments. Finally, results from simulations of the fragmentation of steel containers due to explosively expanding gases are presented. The results show that MPM can be used as an alternative method for simulating high strain-rate, large deformation impact, penetration, and fluid-structure interaction problems.

1 INTRODUCTION

Dynamic failure of metals has been the focus of considerable experimental investigation (Curran and Seaman [1] and references therein). Computational modeling and simulation of complex impact, penetration, and fragmentation problems has become possible with the rapid improvement in computational tools and power (see Zukas [2] for a survey of tools available in 1990). The computational codes used for the simulation of these problems can be classified as Eulerian or Lagrangian with advantages and disadvantages (Anderson and Bodner [3]) depending upon the framework used. Recent simulations of impact, ductile failure, and fragmentation have tended to use Lagrangian approaches (Camacho and Ortiz [4], Johnson et al. [5]) with special techniques for simulating fracture and failure.

In this work, impact, penetration, and fragmentation of metals is simulated using the Material Point Method (MPM) (Sulsky et al. [6, 7]). MPM is a particle method for structural mechanics simulations. In this method, the state variables of the material are described on Lagrangian particles or “material points”. In addition, a regular structured grid is used as a computational scratch pad to compute spatial gradients and to solve the governing conservation equations. The grid is reset at the end of each time step so that there is no mesh entanglement. An explicit time-stepping version of MPM has been used in the simulations of impact, penetration, and fragmentation presented in this work.

2 APPROACH

The MPM algorithm used in this work is based on the description of Sulsky et al. [7] with modifications and enhancements including modified interpolants (Bardenhagen and Kober [8]) and frictional contact (Bardenhagen et al. [9]). The computations have been performed using the massively parallel Uintah Computational Framework (UCF) (de St. Germain et al. [10]) that uses the Common Component Architecture paradigm (Armstrong et al. [11]).

A hypoelastic-plastic stress update approach (Zocher et al. [12]) has been used with the assumption that the rate of deformation tensor can be additively decomposed into elastic and plastic parts. This choice can be justified because of the expectation of relatively small elastic strains for the problems under consideration. Two plasticity models for flow stress are considered along with a two different yield conditions. Explicit fracture simulation is computationally expensive and prohibitive for the large simulations under consideration. We have chosen to use porosity, damage models, and stability criteria for the prediction of failure (at material points) and particle erosion for the simulation of fracture propagation.

A particle is tagged as "failed" when its temperature is greater than the melting point of the material at the applied pressure. An additional condition for failure is when the porosity of a particle increases beyond a critical limit. A final condition for failure is when a bifurcation condition such as the Drucker stability postulate is satisfied. Upon failure, a particle is either removed from the computation by setting the stress to zero or is converted into a material with a different velocity field which interacts with the remaining particles via contact. Either approach leads to the simulation of a newly created surface.

2.1 Models

The Cauchy stress in the solid is partitioned into volumetric and deviatoric parts. Only the deviatoric part of stress is used in the plasticity calculations assuming isoschoric plastic behavior. The hydrostatic pressure is calculated either using the elastic moduli or from a temperature-corrected Mie-Gruneisen type equation of state (Zocher et al. [12]). The shear modulus and melting temperature are pressure and temperature-dependent (Steinberg et al. [13]). Two temperature and strain rate dependent plasticity models have been used - the Johnson-Cook model (Johnson and Cook [14]) and the Mechanical Threshold Stress (MTS) model (Follansbee and Kocks [15], Goto et al. [16]). In addition, two yield criteria have been explored - the von Mises condition and the porosity-dependent Gurson-Tvergaard-Needleman (GTN) yield condition (Gurson [17], Tvergaard and Needleman [18]). An associated flow rule is used to determine the plastic rate parameter in either case. The evolution of porosity is calculated as the sum of the rate of growth and the rate of nucleation (Chu and Needleman [19]). Part of the plastic work done is converted into heat and used to update the temperature of a particle (Borvik et al. [20]). An equation for the dependence of specific heat upon temperature is used when modeling steel. The heat generated at a material point is conducted away at the end of a time step using the heat equation. After the stress state has been determined, a scalar damage parameter is updated using either the Johnson-Cook damage model (Johnson and Cook [21]). The determination of whether a particle has failed is made on the basis of either or all of the following conditions: (1) the particle temperature exceeds the melting temperature, (2) the TEPLA-F fracture condition (Johnson and Addessio [22]) is satisfied, and (3) a bifurcation/material stability condition is satisfied. Two stability criteria have been used - the Drucker stability postulate (Drucker [23]) and the loss of hyperbolicity criterion (using the determinant of the acoustic tensor) (Rudnicki and Rice [24], Becker [25]).

3 VALIDATION

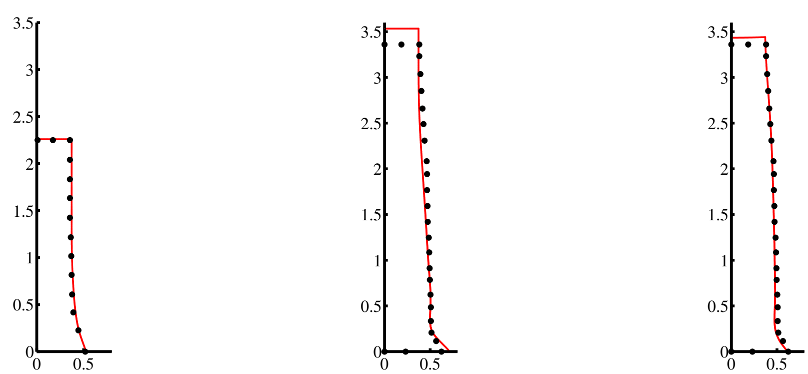
Taylor impact tests have been simulated using MPM to validate the stress update procedure and the Johnson-Cook and MTS plasticity models. Figure 1(a) shows the deformed shape and plastic strain contour (> 0.5) of a 4340 steel cylinder compared with experimental data (Johnson and Cook [21]). The simulation results match experimental data remarkably well. Figures 1(b) and (c) compare the simulated deformed shape of an annealed copper cylinder with experimental data (Zocher et al. [12]). The Johnson-Cook plasticity model has been used for the result shown in Figure 1(b) while the MTS model has been used in Figure 1(c). A Mie-Gruneisen equation of state has been used in both cases. The MTS model performs better than the Johnson-Cook model for this material.

A second validation experiment has been performed by simulating the impact of a 6061-T6 aluminum sphere against a plate attached to a hollow cylinder of the same material (Chhabildas et al. [26]). The experimental setup, and comparisons of free surface velocity and axial strains are shown in Figures 2(a), (b), and (c), respectively. There is some ringing of the cylinder in the simulations, but the overall trend is captured. Some of the difference between the experimental data and the simulations could be because a Johnson-Cook model (Lesuer et al. [27]) was used for the aluminum. The above validation tests show that the MPM code performs as expected.

4 SIMULATIONS

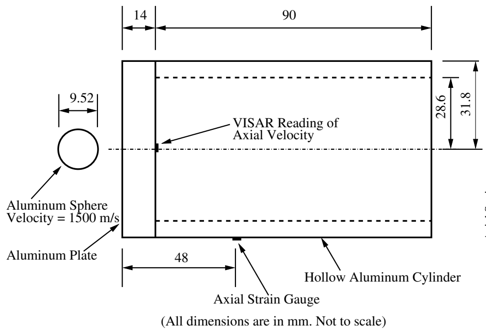
The impact and penetration of a S7 tool steel projectile into an Armco Iron target has been simulated using MPM with two different particle erosion algorithms. The geometry of the test is from Johnson et al. [28] and the material properties have been obtained from Johnson and Cook [21]. The depth of penetration after 160 μs is shown in Figure 3(a) and (b). Both cases use frictional contact. The depth of penetration is less for the case when particles are converted into a new material after failure. Also, the energy balance is better behaved in that case. There is some mesh dependence on the depth of penetration which is currently under investigation.

We have also simulated a coupled fluid-structure interaction problem where a cylinder expands and fragments due to gases generated inside. The dynamics of the solid materials - steel and PBX 9501 - is modeled using MPM. Gas-solid interaction is accomplished using an Implicit Continuous

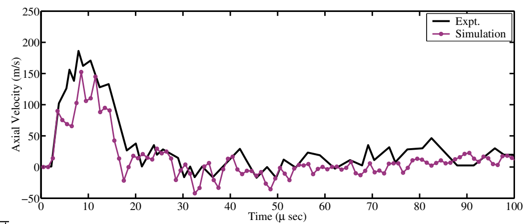


(a) 4340 Steel (Johnson-Cook) (b) Copper (Johnson-Cook) (c) Copper (MTS)

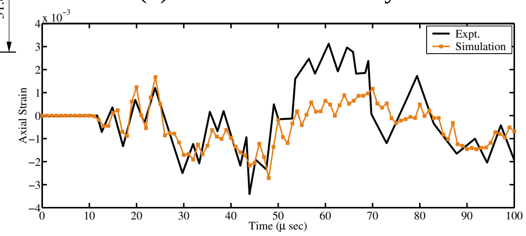
Figure 1: Simulations of Taylor impact tests (dots = experimental data, solid line = simulated data)



(a) Experimental setup.

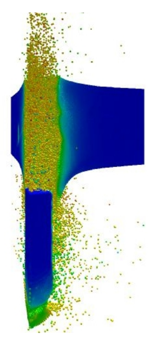


(b) Free surface velocity.

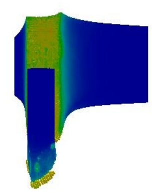


(c) Axial strain.

Figure 2: Simulations of cylinder impact tests.



(a) Stress set to zero upon failure.

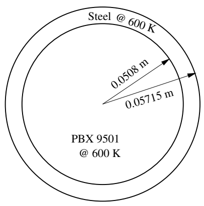


(b) Particles converted upon failure.

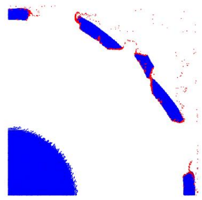
Figure 3: Simulations of penetration (particles colored by plastic strain).

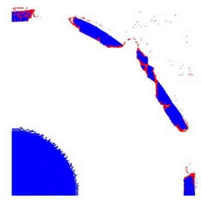
Eulerian (ICE) multi-material hydrodynamic code (Guilkey et al. [29]). A single computational grid is used for all the materials. The first set of simulations was performed using the geometry shown in Figure 4(a). A steel cylinder was used to confine the PBX 9501 material and the simulation was started with both materials at a temperature of 600 K. An initial Gaussian distribution of porosity was assigned to the steel. The fragments of the cylinder after failure (for two steels - 4340 and HY100) are shown in Figures 4(b) and (c). The Johnson-Cook model was used for 4340 steel. The MTS model (Goto et al. [16]) and the GTN yield condition was used for HY100. The expected number of fragments along the circumference matches the analytical prediction by Grady and Hightower [30]. Both steels show similar fragmentation though the exact shape of the fragments differs slightly.

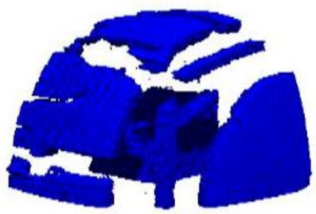
Figure 4(d) and (e) shows the fragmentation obtained from three-dimensional simulations of a 4340 steel cylinder with end-caps containing PBX 9501. The simulation was started with both materials at a temperature of 600 K. A uniform initial porosity was assigned to all steel particles and evolved according to the models discussed in the previous section. Upon failure, the particle stress



(a) Geometry.


(b) 4340 Steel.


(c) HY 100 Steel.


(d) Fragments of the container.

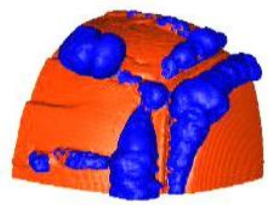

(e) Gases escaping from the container.

Figure 4: Simulations of fragmenting cylinders.

was set to zero. The figures show that these simulations capture some of the qualitative features observed in the experiments on exploding steel cylinders.

5 DISCUSSION AND CONCLUSION

A computational scheme for the simulation of high rate deformation, impact, penetration and and fragmentation using the material point method has been presented. Various impact tests have been used to verify and validate the approach. Simulations of target penetration have shown that energy is better conserved when particles are converted into materials with a different velocity field upon failure (rather than when the stress is set to zero). Some mesh dependence of the results has been observed. Simulations of exploding cylinders in two-dimensions have been compared with analytical solutions for the expected number of fragments and found to provide good agreement. Three-dimensional simulations also show qualitative agreement with experiments. These results show that the material point method is an excellent tool for the simulation of high rate deformation and fragmentation problems.

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